Higgs Production through Sterile Neutrinos

based on arXiv:1512.06035

Oliver Fischer
University of Basel, Switzerland
oliver.fischer@unibas.ch

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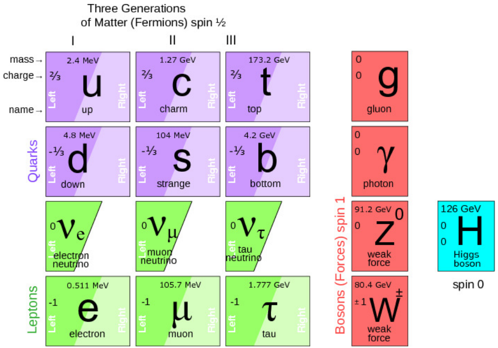
Motivation for sterile neutrinos



- Observation of neutrino oscillations requires *at least* two of the light neutrinos to be massive.
- Neutrino masses can be accounted for efficiently by right-handed or "sterile neutrinos".
- Seesaw formula: $(m_\nu)_{\alpha\beta} = -\frac{1}{2} v_{\mathrm{EW}}^2 \left(Y_\nu^T \cdot M^{-1} Y_\nu\right)_{\alpha\beta}$

The Seesaw Mechanism

- Naïve $(1\ \nu_L,\ 1\ \nu_R)$ version: $m_\nu = \frac{1}{2}\frac{v_{\mathrm{EW}}^2 |y_\nu|^2}{M_R}$
- More realistic example, the $(2\ \nu_L,\ 2\ \nu_R)$ version:

$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ 0 & \mathcal{O}(y_\nu) \end{pmatrix}, \qquad \begin{pmatrix} M_R & 0 \\ 0 & M_R + \varepsilon \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = \frac{v_{\mathrm{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R}(1+\varepsilon)$$

$\Rightarrow$ Knowledge of m_{ν_i} implies a relation between y_ν and M_R.

Lowscale Seesaw

- This example uses a specific structure of the Yukawa and mass matrices that can be realised by symmetries (no fine tuning).
- A $(2\ \nu_L,\ 2\ \nu_R)$ example:

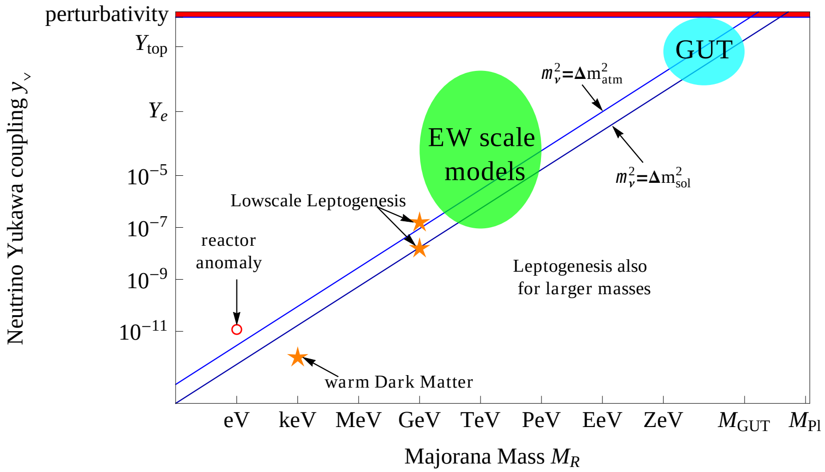
$$Y_\nu = \begin{pmatrix} \mathcal{O}(y_\nu) & 0 \\ \mathcal{O}(y_\nu) & 0 \end{pmatrix}, \qquad \begin{pmatrix} 0 & M_R \\ M_R & \varepsilon \end{pmatrix}$$

$$\Rightarrow m_{\nu_i} = 0 + \varepsilon \frac{v_{\mathrm{EW}}^2 \mathcal{O}(y_\nu^2)}{M_R^2}$$

$\Rightarrow$ In general: no fixed relation between y_ν and M_R.

$\Rightarrow$ Large y_ν are compatible with neutrino oscillations.

The Big Picture



Symmetry Protected Seesaw Scenario

- Assumption: collider phenomenology dominated by two sterile neutrinos N_i with protective symmetry, such that

$$\mathscr{L}_N = -\frac{1}{2}\overline{N_R^1}M(N_R^2)^c - y_{\nu_\alpha}\overline{N_R^1}\widetilde{\phi}^\dagger L^\alpha + \mathrm{H.c.}$$

- The active-sterile mixing parameter: $\theta_\alpha = \frac{y_{\nu_\alpha} v_{\mathrm{EW}}}{\sqrt{2}M}$
- The leptonic mixing matrix to leading order in θ_α

$$\mathcal{U} = \begin{pmatrix} \mathcal{N}_{e1} & \mathcal{N}_{e2} & \mathcal{N}_{e3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_e & \frac{1}{\sqrt{2}}\theta_e \\ \mathcal{N}_{\mu 1} & \mathcal{N}_{\mu 2} & \mathcal{N}_{\mu 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\mu & \frac{1}{\sqrt{2}}\theta_\mu \\ \mathcal{N}_{\tau 1} & \mathcal{N}_{\tau 2} & \mathcal{N}_{\tau 3} & -\frac{\mathrm{i}}{\sqrt{2}}\theta_\tau & \frac{}{\sqrt{2}}\theta_\tau \\ 0 & 0 & 0 & \frac{\mathrm{i}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\theta_e^* & -\theta_\mu^* & -\theta_\tau^* & -\frac{\mathrm{i}}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) & \frac{1}{\sqrt{2}}\left(1-\frac{\theta^2}{2}\right) \end{pmatrix}$$

Interactions between heavy neutrinos and the SM

- **Charged current** (CC):

$$j^{\pm}_{\mu} = \frac{g}{2}\,\theta_{\alpha}\,\bar{\ell}_{\alpha}\,\gamma_{\mu}\,(-\mathrm{i}N_1 + N_2)$$

- **Neutral current** (NC):

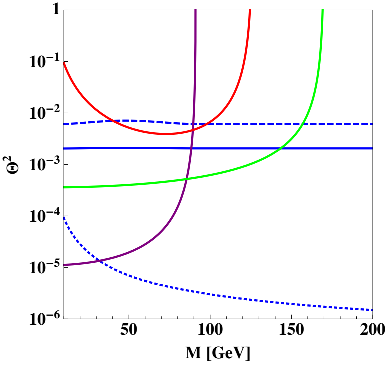
$$j^{0}_{\mu} = \frac{g}{2\,c_W}\left[\theta^2\,\bar{N}_2\gamma_{\mu}\,N_2\; + (\bar{\nu}_i\,\gamma_{\mu}\,\xi_{\alpha 1}\,N_1 + \bar{\nu}_i\,\gamma_{\mu}\,\xi_{\alpha 2}\,N_2\; +\; \mathrm{H.c})\right]$$

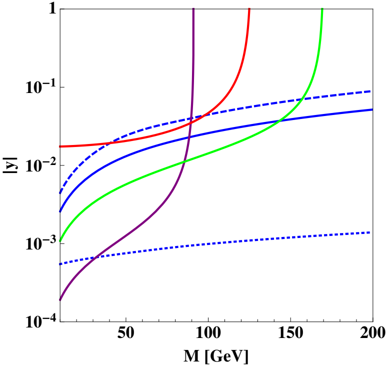
- Higgs boson **Yukawa** interaction:

$$\mathscr{L}_{\mathrm{Yukawa}} = \sum_{i=1}^{3}\xi_{\alpha 2}\,\frac{\sqrt{2}\,M}{v_{\mathrm{EW}}}\nu_i\phi^0\left(\overline{N}_1 + \overline{N}_2\right)$$

- With the mixing parameters: $\xi_{\alpha 1} = (-\mathrm{i})\,\mathcal{N}^{*}_{\alpha\beta}\,\frac{\theta_{\beta}}{\sqrt{2}}$, $\xi_{\alpha 2} = \mathrm{i}\,\xi_{\alpha 1}$

Combination of present bounds





Direct searches

- Delphi (Z pole searches) @2σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- LHC (Higgs decays*) @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- Aleph ($e^+e^- \to 4$ leptons) @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

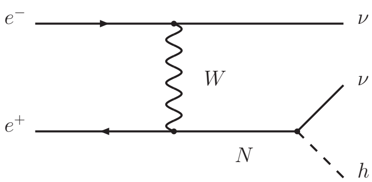
Other (global fit)

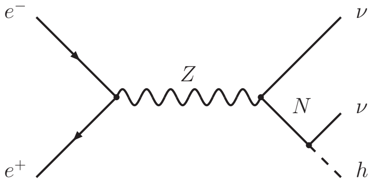
- $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$
- $|y|=|y_{\nu_\mu}|$, $\Theta^2=|\theta_\mu|^2$
- $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$

Antusch, OF; arXiv:1502.05915 (2015)

$*$ Currently dominated by $h \to \gamma\gamma$.

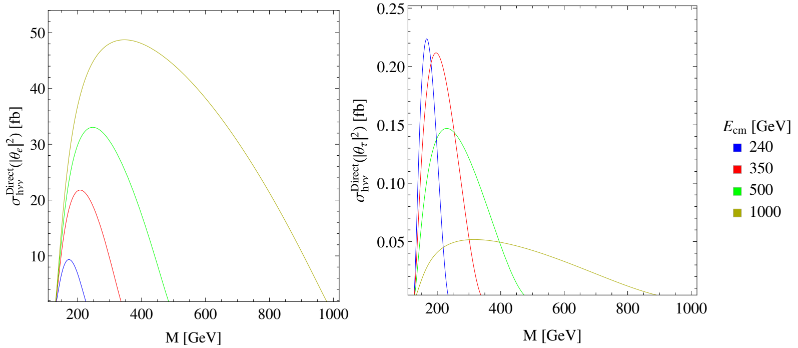
Resonant mono-Higgs from sterile neutrinos





- Generally: $\sigma_{h\nu\nu} = \sigma_{h\nu\nu}^{\text{SM}} + \sigma_{h\nu\nu}^{\text{Non-U}} + \sigma_{h\nu\nu}^{\text{Direct}}$.
- $\sigma_{h\nu\nu}^{\text{Direct}}$ from on-shell production of sterile neutrinos.
  - ⋆ Interference with SM-background strongly suppressed.
  - ⋆ W-exchange process effective at larger centre-of-mass energies, but sensitive only to y_{ν_e}.
  - ⋆ s-channel production (Z boson) produces all flavours.
- $\sigma_{h\nu\nu}^{\text{Non-U}}$: indirect effect (via input parameters) from the induced non-unitarity of the PMNS matrix.

Resonant mono-Higgs-production cross section



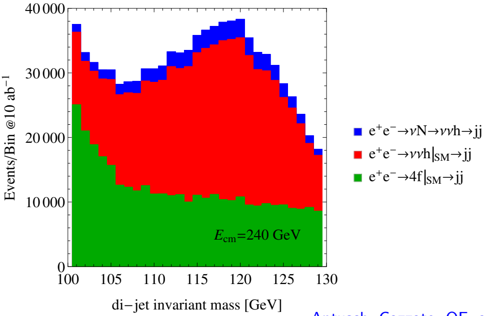
Antusch, Cazzato, OF, arXiv:1512.06035 (2015)

- Using present upper bounds at 68% Bayesian confidence level.
- Mono Higgs production cross section in the SM is $\sim$ 54 fb at 250 and 350 GeV

Simulation, reconstruction and kinematic cuts

- Event simulation: WHIZARD 2.2.7
- Showering: PYTHIA 6.427
- Reconstruction: Delphes 3.2.0 (ILD card)
- Anaylsis: Madanalysis5

The Higgs Peak: $|y_{\nu_e}| = 0.036$ & $M = 152$ GeV, 10 ab^{-1}



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Our cuts (not fully optimised):

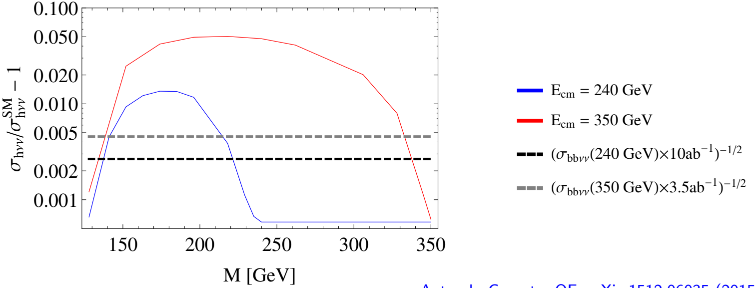
- Pre selection: $N_j = 2, N_\ell = 0$, $110 < M_{jj} < 125$ GeV
- For the example: $P_{jj} > 70$, $\not{E}_T > 15$ GeV

Event counts: (starting with pre selection)

BKG	548.584	$\rightarrow$	18.627
$\sigma^{\text{Direct}}_{h\nu\nu}$	15.335	$\rightarrow$	4.846

$$\Rightarrow \frac{S}{\sqrt{S+B}} \simeq 30!$$

Contamination of SM parameters

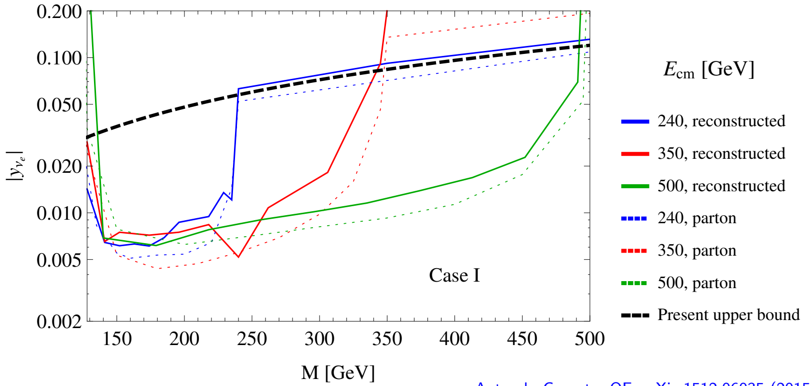


Antusch, Cazzato, OF, arXiv:1512.06035 (2015)

Standard cuts for Higgs events at lepton colliders:

$\sqrt{s}$	240 GeV	350 GeV
Missing Mass [GeV]	$80 \leq M_{\mathrm{miss}} \leq 140$	$50 \leq M_{\mathrm{miss}} \leq 240$
Transverse P [GeV]	$20 \leq P_T \leq 70$	$10 \leq P_T \leq 140$
Longitudinal P [GeV]	$\lvert P_L \rvert < 60$	$\lvert P_L \rvert < 130$
Maximum P [GeV]	$\lvert P \rvert < 30$	$\lvert P \rvert < 60$
Di-jet Mass [GeV]	$100 \leq M_{jj} \leq 130$	$100 \leq M_{jj} \leq 130$
Angle (jets) [Rad]	$\alpha > 1.38$	$\alpha > 1.38$

Sensitivity of the mono-Higgs channel to neutrino mixing



Antusch, Cazzato, OF, arXiv:1512.06035 (2015)

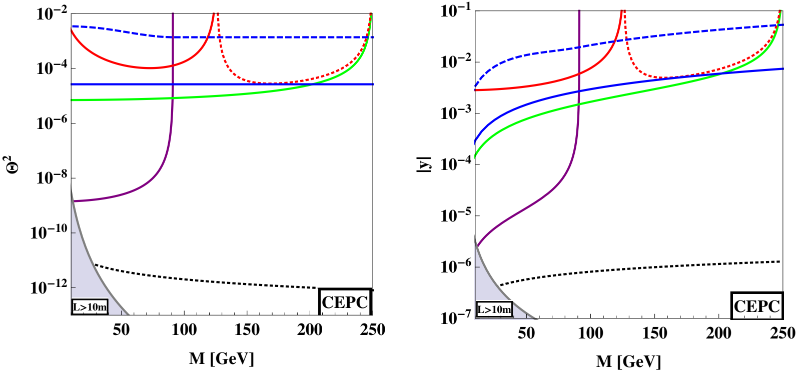
Considered:
10 ab^{-1} for 240 GeV, 3.5 ab^{-1} for 350 GeV, 1 ab^{-1} for 500 GeV

Summary and conclusions

- Sterile neutrinos are well motivated extensions of the SM.
- Symmetry protected scenarios allow for large Yukawa couplings and masses in the interesting range.
- **Higher center-of-mass energies lead to increased mono-Higgs production cross sections from sterile neutrinos.**
- $\sqrt{s} =$ **350 GeV is even more sensitive than 240 GeV.**
- A contamination of the Higgs sample can lead to a 3σ deviation of the SM parameters.
- Sensitivity to $|y_{\nu_e}|$ down to 6×10^{-3} is possible.
  - ⋆ **Important for understanding the data.**
  - ⋆ **Complementarity** to other searches for sterile Neutrinos.
- For other search channels, see: Antusch, OF; arXiv:1502.05915 (2015)

Thank you for your attention.

Backup I: Prospects of Sensitivity at the CEPC



Direct searches

- Z pole search @2σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- Higgs $\to$ WW @1σ: $|y|=\sqrt{\sum_\alpha |y_{\nu_\alpha}|^2}$, $\Theta^2=\sum_\alpha|\theta_\alpha|^2$
- $e^+e^- \to h + ME_{(T)}$ @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$
- $e^+e^- \to l\nu l\nu^*$ @1σ: $|y|=|y_{\nu_e}|$, $\Theta^2=|\theta_e|^2$

Other

- Precision constraints: $|y|=\sqrt{|y_{\nu_e}|^2+|y_{\nu_\mu}|^2}$, $\Theta^2=|\theta_e|^2+|\theta_\mu|^2$
- Precision constraints: $|y|=|y_{\nu_\tau}|$, $\Theta^2=|\theta_\tau|^2$
- "Unprotected" type−I seesaw

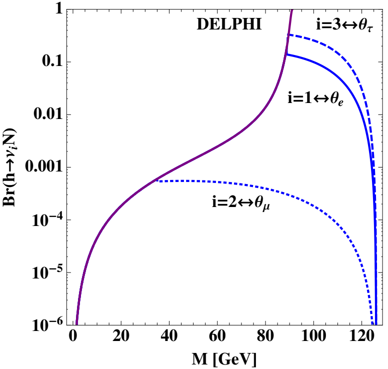
Antusch, OF; arXiv:1502.05915 (2015)

∗ Preliminary estimate using statistical uncertainty only.

Backup II: Higgs Boson Branching Ratio into Neutrinos

- From "indirect" tests and Delphi.
- $\mathcal{O}(1)$ branching ratio possible.

$\Rightarrow$ Possible effect on Higgs decay rates into Standard Model particles.



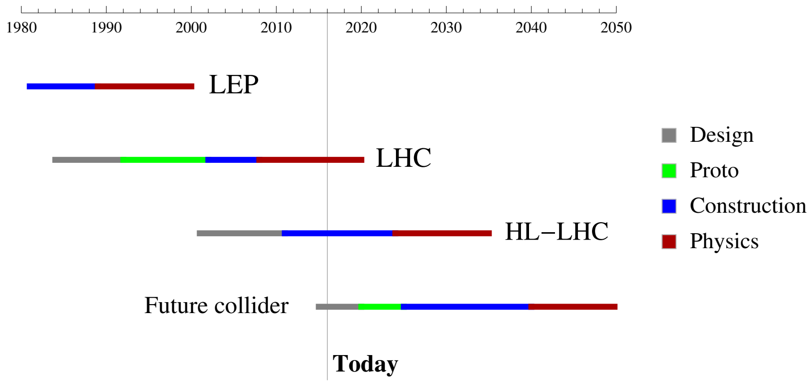
Antusch, OF; arXiv:1502.05915 (2015)

Backup III: Cross sections for SM background

Final state	$\sigma^{\rm SM}$@240 GeV	$\sigma^{\rm SM}$@350 GeV	$\sigma^{\rm SM}$@500 GeV
$b\bar{b}\nu\nu$	146.492	134.614	183.594
$c\bar{c}\nu\nu$	88.0172	73.7956	82.7041
$jj\nu\nu$	528.8	463.1	500.3
$b\bar{b}b\bar{b}$	81.2629	47.6152	25.5571
$b\bar{b}c\bar{c}$	146.566	87.6518	51.6446
$b\bar{b}jj$	6820.6	4259.5	2537.8
$b\bar{b}e^+e^-$	2080.87	2500.82	2920.9
$b\bar{b}\tau^+\tau^-$	34.1905	19.7975	11.0619
$c\bar{c}\tau^+\tau^-$	25.2553	15.0695	9.15227
$jj\tau^+\tau^-$	116.0	72.4	37.6
$\tau^+\tau^-\nu\nu$	235.89	163.851	119.989
single top	0.012	63.3	1092
$t\bar{t}$	—	322.	574.

All cross sections in fb.

Backup IVa: High Energy Physics Time Scales



Backup IVb: High Energy Physics Time Scales